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Research Article

Mapping of nutrient regulating ecosystem service supply and demand on different scales in Schleswig-Holstein, Germany

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Abstract

This study deals with one of the regulating ecosystem services, nutrient regulation. In order to guarantee sustainable land management, it is of great relevance to gain spatial information on this ecosystem service. Unsustainable land management with regard to nutrient regulation may, for example, result in eutrophication which has been identified as a major threat for the environmental state of our water bodies. In the first step of research, the potential supplies and demands of/for nutrient regulation were assessed and mapped at two different spatial scales: The German federal state of Schleswig-Holstein (regional scale) and the Bornhöved Lakes District (local scale). The assessment was undertaken for nitrogen, as an exemplary nutrient. Subsequently, potential supply and demand, combined with the nitrate leaching potential and the groundwater nitrate concentration, were incorporated into a correlation analysis. The data was statistically analysed with varying pre-processing and spatial resolutions. The statistical analysis reveals that large scale data with low resolution leads to more uncertain results. Decreasing the spatial scale and increasing the resolution of the data through a spatially more explicit assessment, leads to

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more explicit results. It is striking that the study reveals a spatial mismatch between the potential supply and demand for the ecosystem service nutrient regulation, which denotes unsustainable land management in the study areas.

Keywords

Bornhöved Lakes District, eutrophication, fertiliser application, nitrogen budget, groundwater nitrate concentration, nutrient status, correlation analysis, local scale, regional scale

Introduction

The availability of nutrients is essential for living organisms such as plants, animals and bacteria. With regard to agricultural production, nutrients are applied to agricultural grounds in order to guarantee high yields (Vitousek et al. 2009, Power 2010, Tilman 1999, Tivy 1987). The increasing demand for agricultural products has led to increasing fertilisation (Tilman 1999, Tivy 1987). Unfortunately, it is common practice that, through fertilisation, the amount of nutrients available in the soil exceeds the actual requirements of the crop (Tilman 1999) which leads to over-fertilisation (Vitousek et al. 2009, Tivy 1987). The consequence of a persistent surplus of nutrients results in degradation of the environment (Chapin et al. 2002, Fenn et al. 1998). More precisely, the excess of nutrients on agricultural land leads to increasing nutrient losses from the soil and consequently enrichment of nutrients in groundwater, lakes, rivers and eventually the ocean (Chapin et al. 2002, Vitousek et al. 1997, Tivy 1987). Therefore, the eutrophication of ecosystems has been recognised as a severe issue by society as well as research, whereby agriculture has been defined as the major diffuse source of nutrient inputs into the environment (Trepel 2016, TEEB 2015, Taube et al. 2013, Larsson and Granstedt 2010, HELCOM 2004). On the political level of the European Union, there are different directives aiming to decrease nutrient inputs, such as the Nitrate Directive (European Council 1991), Water Framework Directive (European Parliament and Council of the European Union 2000) and Groundwater Directive (European Parliament and Council of the European Union 2006). In 2016, the European Commission took legal action against Germany for failing to take stronger measures to combat water pollution by nitrates as data on nitrate concentration in ground and surface waters were worsening (European Commission 2016).

Sustainable management of nitrogen is of great importance for agroecosystems, as insufficient nitrogen inputs will decrease crop production while an excess input will pollute the environment (Withers et al. 2014, Tilman 1999). According to the LLUR (2014)[*1] in Schleswig-Holstein, the groundwater bodies of more than 7500 km² have a poor chemical status in the main aquifer, primarily due to nitrate pollution. This area equals approximately half of the federal state's spatial extent. In order to combat eutrophication efficiently and to improve the status of the environment, it is necessary to generate (spatially) explicit data on nutrient inputs (Selman and Greenhalgh 2009, Ondersteijn 2002, European Council

1991). Much of recent literature deals with nutrient oversupply and its consequences for the environment (e.g. Taube et al. 2015, Wendland et al. 2014, Withers et al. 2014, Larsson and Granstedt 2010, Tilman 1999).

Spatial ecosystem service analyses can be used to increase the understanding of the interrelations between human activities, e.g. land management and the environment. Therefore, the European Union has asked all its member states to map and assess the states of their ecosystems and the services they provide within the Biodiversity Strategy to 2020[*2] (Maes et al. 2012). Ecosystem service analyses are qualified to support sustainable land management (Smith et al. 2012), as the capacity of ecosystems to produce desired benefits is assessed.

The underlying concept commonly differentiates amongst 3 categories of ecosystem services: regulating, provisioning and cultural services. All these ecosystem services contribute to human well-being (i.e. Burkhard and Maes 2017, Burkhard et al. 2012b, de Groot et al. 2010, Kandziora et al. 2013, Landuyt et al. 2012, Millennium Ecosystem Assessment 2005). In this study, the concept of ecosystem services is applied to the topic of nutrient regulation. Recent ecosystem service research, with regard to nitrogen, identifies nitrate leaching into fresh waters as the consequence of "…overloading the regulating service […] naturally provided by soils of all habitats…" (Jones et al. 2014, p. 81). In the context of this research, nutrient budgets were calculated by using nutrient nitrogen as an example. A statistical evaluation was undertaken whereby the data on the potential supply and demand for nutrient regulation was combined with data on the nitrate leaching potential and the groundwater nitrate concentration.

Following the problems described above, the objectives and corresponding research questions of the study are:

1. Assessing the potential supply and demand of nutrient regulation in the study areas. Do potential supplies and demands of/for nutrient regulation coincide in Schleswig-Holstein and the Bornhöved Lakes District?
2. Testing the statistical relation between the nitrogen budget, nutrient regulation potential, nitrate leaching potential and the actual nutrient status of the study areas. Is it possible to statistically prove the influence of the ecosystem service nutrient regulation on the nutrient status?
3. Giving useful advice on the usability of the different methodologies and scales assessed. Does higher resolution data result in more valid outcomes?

This study is part of the EU-funded Horizon 2020 Support and Coordination Action ESMERALDA[*3]. Within this project, various methods for mapping and assessment of ecosystems and their services have been identified. Selected methods are tested in case studies which are representative for different biomes, spatial scales, ecosystem types and services as well as policy questions across Europe. Our methods and case study is part of the testing and contributes to the implementation of the EU Biodiversity Strategy to 2020.

In the following chapter, background information is given on the topic of ecosystem services. Thereafter, the two study areas are described. Chapter 3 outlines the methods which were applied in this study. Furthermore, relevant datasets are specified. In Chapters 4 and 5, the results of the study are presented and discussed, respectively. Conclusions are drawn in Chapter 6, based on the objectives defined in the introduction.

Background information

The following section, gives information on the applied ecosystem service concept, nutrient regulation and the study areas.

The ecosystem service concept and nutrient regulation

Research on ecosystem services has been prospering in recent years. The fast evolution in this field of science results in divergences with regard to definitions and terminologies. Ecosystem services have been defined by de Groot et al. (2010) as direct and indirect contributions to human well-being that originate from ecosystems. Burkhard et al. (2012b) (p. 2) defined ecosystem services as “the contributions of ecosystem structure and function - in combination with other inputs - to human well-being”. Fig. 1 depicts the interrelations and dependencies between the ecosystem and human benefits through ecosystem services within a defined system. The supply of ecosystem services is strongly dependent on ecosystem properties and conditions (Fig. 1). Ecosystem service supply can be specified as potentials (or capacities) and flows (Syrbe et al. 2017, Burkhard et al. 2014, Schröter et al. 2014; see Table 1).

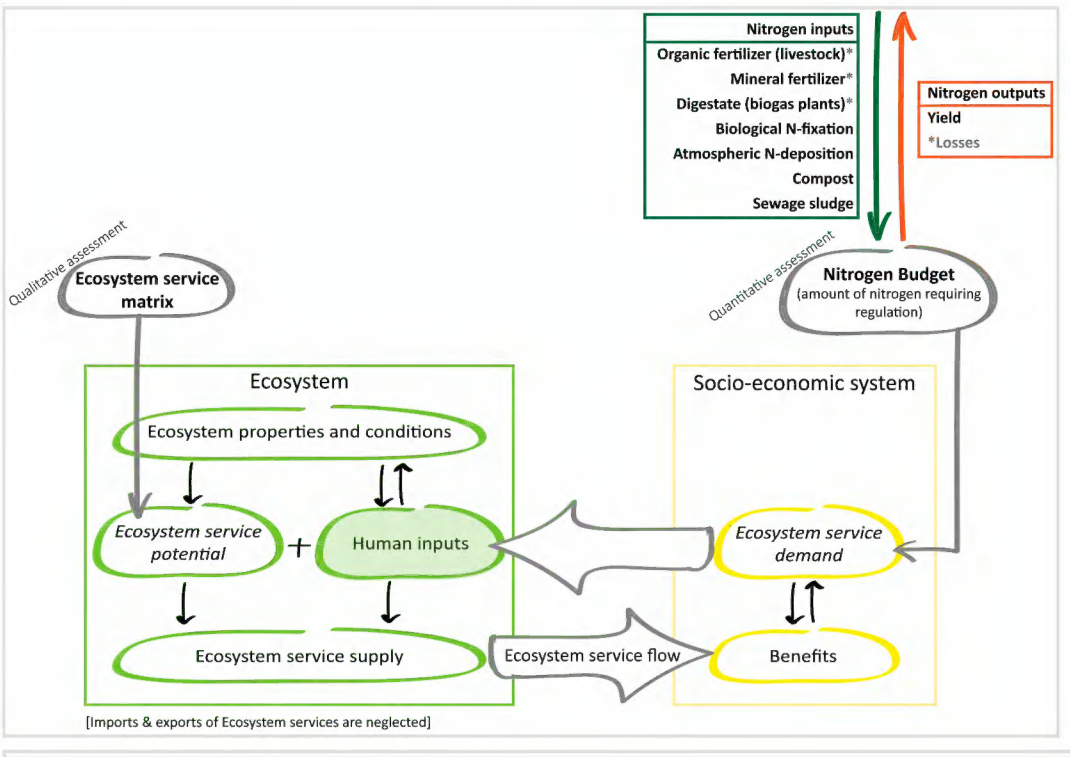

Figure 1.

Ecosystem service mapping framework (based on Syrbe et al. 2017; aspects presented in italic were assessed in this study).

Table 1.

Definitions used within the approach.

Ecosystem service potential Ecosystem service potentials are related to the hypothetical maximum yield of selected ecosystem services (Burkhard et al. 2012a), which are commensurate with the theoretical capacity of an ecosystem to provide a service (Wiggering et al. 2016, Bastian et al. 2012). After von Haaren et al. (2014), the ecosystem service potential can be described as 'offered ecosystem service'. In other words, an ecosystem service potential is the overall available service of a certain ecosystem, but the potential service does not need to be utilised (Bastian et al. 2013). This definition depicts the ecosystem service as stock (Burkhard et al. 2014).
Ecosystem service flow The ecosystem service flow describes the utilised service in a specific area and within a defined period of time (Syrbe et al. 2017, Burkhard et al. 2014, von Haaren et al. 2014). Thus, the flow measures the effective extraction (Syrbe et al. 2017, Bastian et al. 2012). The ecosystem service flow includes effects derived from additional anthropogenic inputs (Syrbe et al. 2017, Burkhard et al. 2014).
Ecosystem service demand Burkhard et al. (2012a) (p. 18) define the demand for ecosystem services as the "[…] sum of all ecosystem goods and services currently consumed or used in a particular area over a given time period." They state that "[…] up to now, demands are assessed not considering where ecosystem services actually are provided" (Burkhard et al. 2012a, p. 18). Syrbe et al. (2017) define the ecosystem service demand as the need for an ecosystem service by society as a whole, particular stakeholder groups or individuals, thus linking the ecosystem service to particular beneficiaries. They identify the risk that sometimes beneficiaries might not be aware of their demand for a certain ecosystem service, particularly with regard to some regulating ecosystem services.

The beneficiaries of the ecosystem service nutrient regulation are diverse. At first sight, it is obvious that society as such is a beneficiary as it strives for a clean environment (Villamagna et al. 2013). With regard to directives and regulations arising from national as well as European legislation, politics can also be defined as a beneficiary for the assessed ecosystem service, which can eventually also be allocated to society as such. Following the approach of Power (2010), agriculture as such simultaneously provides and consumes ecosystem services. In order to provide high yields amongst others, the agricultural system, also known as the agroecosystem, requires the ecosystem service nutrient regulation (Burkhard et al. 2012a, Power 2010). These different applicable perspectives on the beneficiaries of the ecosystem service nutrient regulation emphasise the importance of the service and, as a consequence, underline the demand for its evaluation.

Nutrient regulation

Nutrient regulation is the ability of an ecosystem to recycle nutrients (Burkhard et al. 2014) and is of significant relevance regarding land management. According to Tivy (1987), unmanaged ecosystems are thought to reach a 'steady-state' with regard to the nutrient pool. Losses, as well as inputs, of nutrients are small and in balance (Chapin et al. 2002, Hedin et al. 1995, Tivy 1987). Thus, the nutrient cycle is almost closed (Chapin et al. 2002). However, intense agricultural usage has greatly changed the natural nutrient cycle (Vitousek et al. 1997). Due to fertiliser use and high production yields, the nutrient cycle has been artificially opened up (Chapin et al. 2002, Tivy 1987). As a result, affected areas suffer from the consequences of either nutrient deficiency or oversupply. In order to

guarantee human health and food security, society strives to prevent these circumstances. Nutrient regulation or retention should combat either nutrient deficiency or nutrient oversupply in order to secure a sustainable nutrient cycle (Tivy 1987). Therefore society has a demand for the ecosystem service nutrient regulation. Nutrient regulation varies for different ecosystems. In particular, natural ecosystems such as forests and grassland have a high potential for nutrient regulation (Fu et al. 2012, Burkhard et al. 2014). Besides LULC, other factors are of relevance for determining the potential of nutrient regulation, such as the slope (Fu et al. 2012) and climatic conditions. In our study, next to the assessment of the nutrient regulation potential, we focus on a spatially explicit quantification of the demand for the ecosystem service nutrient regulation.

Study Areas

The following section describes the two study areas: the federal state of Schleswig-Holstein and the Bornhöved Lakes District, both located in northern Germany. We selected these two study areas of different spatial extent in order to allow for some comparisons with regard to the issue of scale. In the first step, we assessed both case study areas with the exact same data and spatial resolution. Thus, in that case, the results of the Bornhöved Lakes District are simply an extract of the results for the federal state of Schleswig-Holstein. In the second step, we used a higher spatial resolution to assess the situation in the Bornhöved Lakes District.

Schleswig-Holstein

Schleswig-Holstein is the northernmost federal state of the Federal Republic of Germany (Fig. 2). The federal state has an area of 15,803 km² (*Statistikamt Nord*[*4]). To the west and east, Schleswig-Holstein is surrounded by the North Sea and the Baltic Sea, respectively. Thus, the climatic conditions in the federal state are maritime and humid with an annual mean temperature of approximately 8°C and precipitation averages of around 840 mm (Climate Data Center 2017). Its geological as well as geomorphological conditions are highly influenced by the final two glaciations of the last glacial period (Pleistocene) (Schott 1956). Both the Saalian and the Weichselian glaciation formed the current landscapes and led to the differentiation within the federal state (Schott 1956). The current landscapes can be divided roughly into three main regions (Bähr and Kortum 1987, Stewig 1982): *Hügelland*[*5] in the eastern part, *Geest* concentrated in the centre and *Marsch* in the western part of Schleswig-Holstein (Fig. 2).

In particular, the varying expansions of the glaciers during the two glaciation periods resulted in the current conditions (Schott 1956, Stewig 1982). The glacial influence can still be recognised in the area of the *Hügelland*, as the rolling hills formed by the moraines and small lakes as well as deep embayments prevail in the landscape (Bähr and Kortum 1987, Stewig 1982, Schott 1956). Contrary to the fertile soils of the *Marsch* and *Hügelland*, the *Geest* is characterised by sandy soils, as the area embodies the outwash plains of the Weichselian glaciation (Bähr and Kortum 1987, Schott 1956). In conjunction with additional erosion, a landscape evolved featuring only little relief. Unlike these two landscape forms,

the *Marsch* can be attributed to the Holocene and is thus the youngest of the three landscape types (Hoffmann 2004, Stewig 1982). The *Marsch* area is a low lying area where drainage predominates the landscape (Hoffmann 2004). The federal state is divided into administrative units. These are important in the context of decision-making as well as data availability. The most relevant administrative units for this study are municipalities (Fig. 3), which are the smallest administrative units.

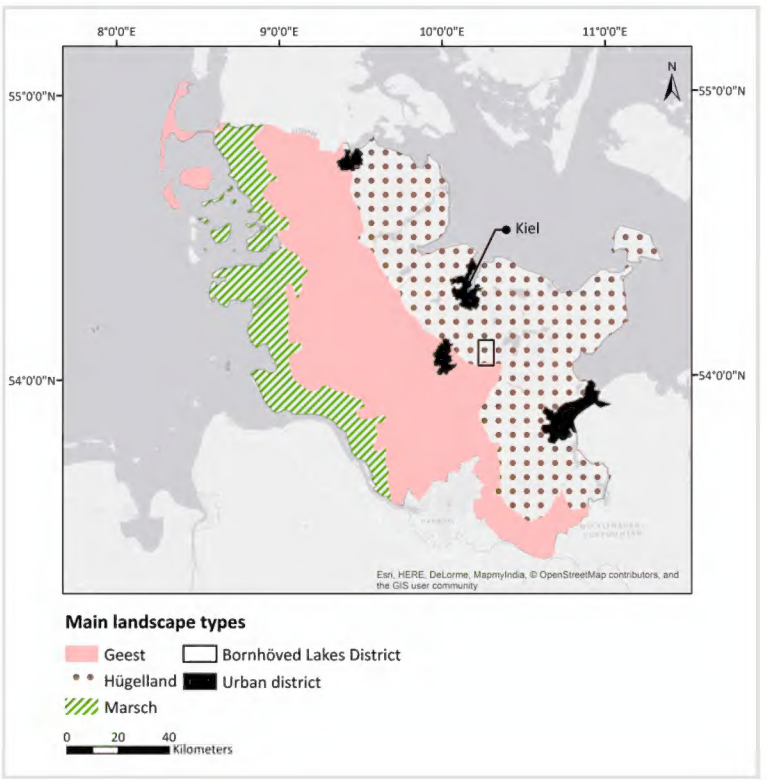

Figure 2.

Schleswig-Holstein study area, showing the differentiation between main landscape types (based on data from LLUR 2017[*6]).

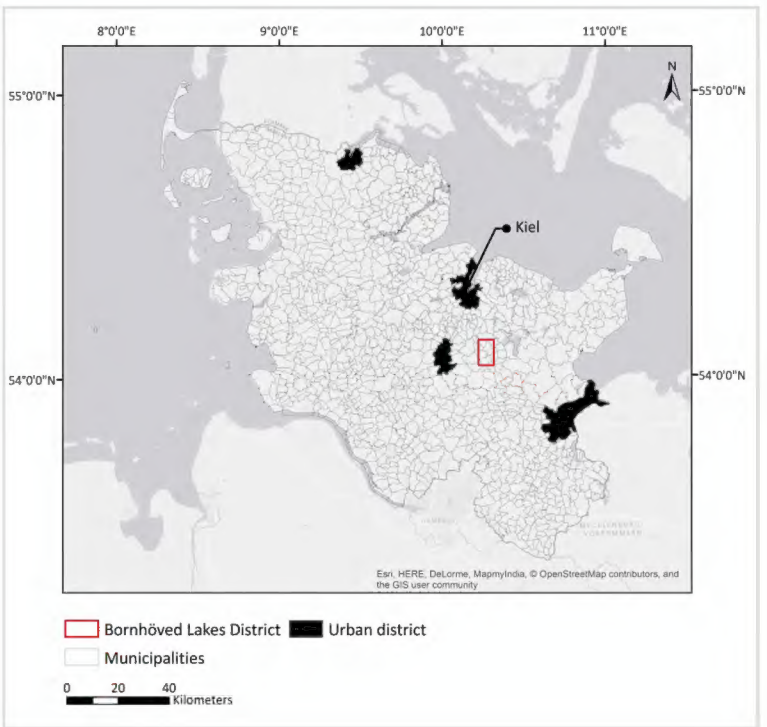

Figure 3.

Assessment units for Schleswig-Holstein: Municipalities (data on administrative boundaries from GeoBasis-DE / BKG 2017b).

Bornhöved Lakes District

The Bornhöved Lakes District is located approximately 30 km south of the city of Kiel, on the border between the landscape regions *Hügelland* and *Geest* (Fig. 2). The appearance and characteristics of the landscape have been influenced greatly by the Weichselian glaciation (Fränzle et al. 2008). In the study area, six glacially formed lakes can be found which are surrounded by forest and agricultural areas (Fränzle et al. 2008). The extent of the Bornhöved Lakes District, which has been defined as a case study area for ecosystem services research, is approximately 60 km² (Kandziora et al. 2013). The Bornhöved Lakes District has already been identified as a case study area in several completed and current research and monitoring projects (Kandziora et al. 2013, Müller et al. 2006, Fränzle et al. 2008). According to Fränzle et al. (2008) and Fohrer and Schmalz 2012, the Bornhöved Lakes District can be regarded as a representative landscape for northern Germany.

Materials and methods

All spatial analyses were executed with the GIS Software ArcMap 10.3. We primarily used the toolboxes *Analysis Tools, Geostatistical Analyst Tools* and *Spatial Analyst Tools*. For statistical computation, we used the software R with the development environment RStudio. The package *dplyr* was used in order to simplify the handling of large datasets. For statistical computations, the package *corrplot* was crucial. Due to data availability, we preferred data from the year 2010 as input data. However, if no data were available for that time period, proximate time periods were selected.

Supply of nutrient regulation

The assessment of the potential supply of the ecosystem service nutrient regulation is based on the ecosystem service matrix by Burkhard et al. (2014). The matrix can be used to distinguish nutrient regulation for different land cover types. CORINE land cover data[*7] from the European Union was selected as the underlying dataset. The CORINE dataset is hierarchically organised into three levels differentiating in total between 44 land cover classes (EEA 1995). In this study, the 2012 CORINE dataset in ArcGIS polygon shape format was applied. Fig. 4 presents the spatial distribution of the CORINE land cover classes in the two study areas. For both study areas, Schleswig-Holstein and the Bornhöved Lakes District, non-irrigated arable land and pastures are the dominant land use/land cover (LULC) classes (Fig. 4). Hotspots of continuous urban fabric, discontinuous urban fabric and industry or commercial units are agglomerated around the four urban districts of Lübeck, Kiel, Flensburg and Neumünster and in the area adjacent to Hamburg in the southwest of the study area. More natural LULC classes are distributed rather randomly in both areas.

CORINE land cover classes were chosen as geospatial units to be placed in the rows (y-axis) of the ecosystem services matrix (Burkhard et al. 2014). For each land cover type occurring in the study area, the corresponding potential for nutrient regulation, derived from

an expert-based assessment, was specified on a relative scale from zero to five by Burkhard et al. (2012a), where five stands for the highest potential. The expert-based assessment was not executed specifically for this study but the potentials have been adopted from the study by Burkhard et al. (2012a). By means of ArcMap 10.3, the values assigned to the CORINE land cover classes were presented in ecosystem service maps for the study areas.

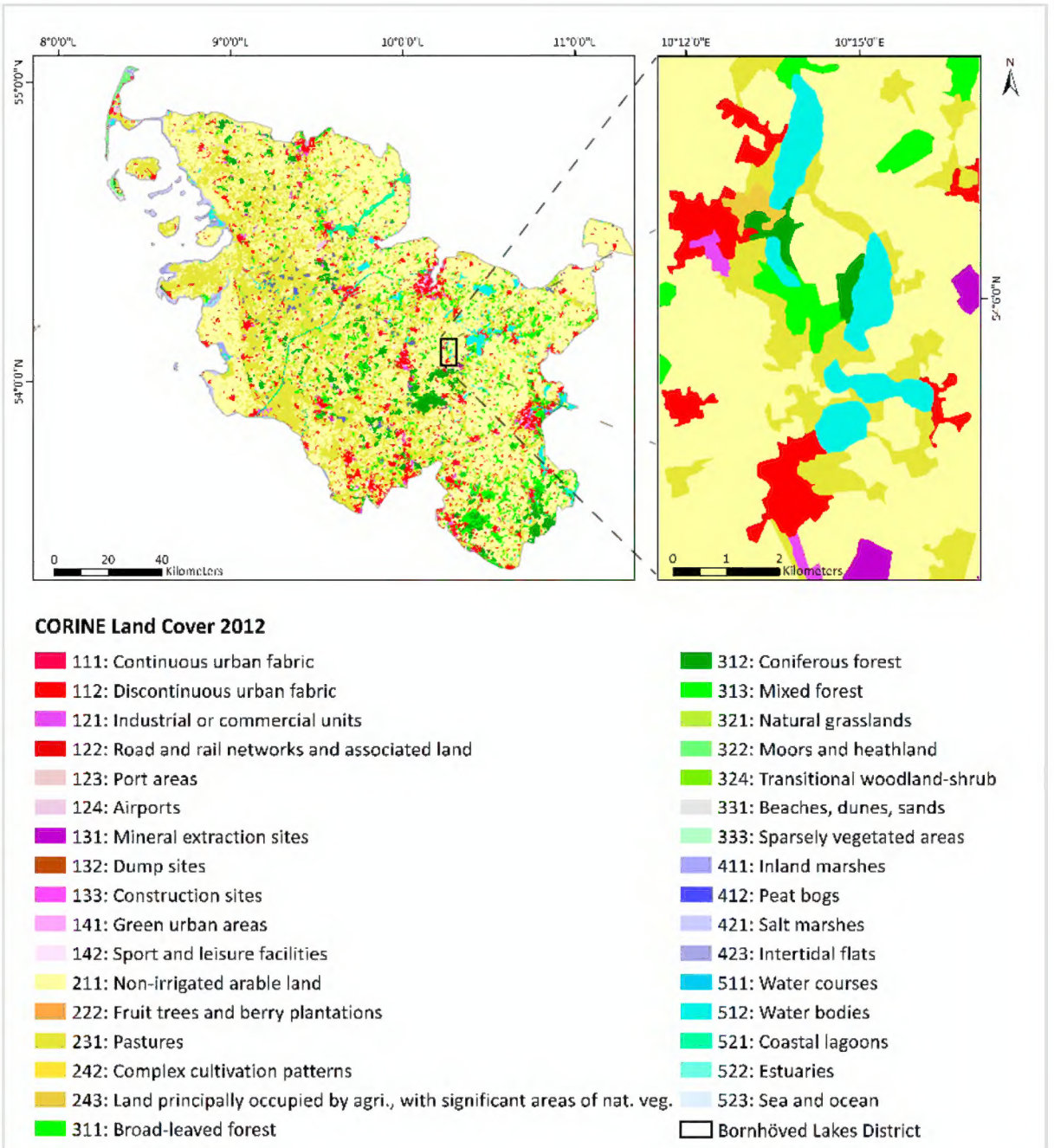

Figure 4.

Distribution of CORINE land cover classes in 2012 in Schleswig-Holstein (left) and the Bornhöved Lakes District (right; data from GeoBasis-DE / BKG 2017a).

Demand for nutrient regulation

In Schleswig-Holstein, the anthropogenic transformation of the nutrient cycle primarily leads to nutrient oversupply, as excess nutrients are introduced into the environment by means of agricultural practices (Trepel 2016, Kreins and Henseler 2015, Taube et al. 2015, Larsson and Granstedt 2010). At these locations, there is a significant demand for the

ecosystem service nutrient regulation. In order to obtain data on the nutrient surplus, we calculated nutrient budgets. Data from the *Landwirtschaftszählung* 2010 (Statistikamt Nord 2010) [*8] served as the basis for the budget calculations. We included the following parameters in the budgets: Organic fertiliser (from livestock) and mineral fertiliser with corresponding losses, compost, biological fixation, nitrogen deposition (UBA 2015), yield, digestate from biogas plants and sewage sludge. An overview on inputs and outputs and on the corresponding methods used for calculating the different parameters is presented in Table 2.

Table 2.

Overview on methodologies and data sources used for the parameters of the nitrogen budget.

Parameter	Indicator with quantification unit	Quantification method and data source	References
Nutrient input	Mineral fertiliser (kg N/ ha*year)	Calculation of mineral fertiliser through estimation of: Mineral Fertiliser=1.06*Yield-0.6*(Organic Fertiliser+Digestate)-0.8*Biological Fixation	Taube et al. (2015), Bach et al. (2014)
	Organic fertiliser from livestock (kg N/ha*year)	Data on livestock from *Landwirtschaftszählung* 2010 (Statistikamt Nord 2010)[*9]; Data on annual N-production through manure from the Ministerium für Landwirtschaft, Umwelt und Verbraucherschutz Mecklenburg-Vorpommern (2008)[*10]	Taube et al. (2013)
	Digestate from biogas plants (kg N/ha*year)	Data on biogas plants from LLUR (2016)[*11] Calculation data for N-formation from digestate related to the average substrate composition (Taube et al. 2013); Reference values (e.g. average performance biogas plants) related to biogas plants in Schleswig-Holstein	Taube et al. (2013)
	Compost (kg N/ha*year)	Constant value from Heidecke et al. (2012)	Heidecke et al. (2012)
	Sewage sludge (kg N/ha*year)	Data on amount of sewage sludge (in 2011) and share applied on agricultural fields from *Ministerium für Energiewende, Landwirtschaft, Umwelt und ländliche Räume Schleswig-Holstein*[*12] (Kleinhans 2013); N-content sewage sludge from Taube et al. (2013)	Taube et al. (2013)
	Biological nitrogen fixation (kg N/ha*year)	Data on land use (grassland and legumes) from *Landwirtschaftszählung* 2010 (Statistikamt Nord 2010); Data on efficiency of nitrogen fixation from Landwirtschaftskammer Niedersachsen (2017a)[*13]	DüV (2007) [*14]

	N-Deposition (wet, dry and occult) (kg N/ha*year)	Data on nitrogen deposition in Germany in 2009 for different land use types from *Umweltbundesamt* (UBA 2015)	-
Nutrient output	Yield (crop and grassland) (kg N/ha*year)	Data on yield for 2010 from *Landwirtschaftszählung* 2010 (Statistikamt Nord 2010); Data on N-content of grass/crop type from DüV (2007)	-
	NH_3 loss from organic fertiliser (%)	Rates on nitrogen application and nitrogen input from Landwirtschaftskammer Niedersachsen (2017b)	DüV (2007)
	Loss through application of mineral fertiliser (%)	Rate for loss through application of mineral fertiliser calculated based on the nitrogen budget by Heidecke et al. (2012)	Heidecke et al. (2012)

Due to the data privacy law, data for some municipalities was not available on the scale of municipalities within the *Landwirtschaftszählung* 2010 (Statistikamt Nord 2010). In order to avoid such data gaps, the available data on the scale of municipalities was compared to the data on the scale of counties. The calculated differences between the two datasets were allocated to the affected municipalities. The relative extent of the agricultural area of the corresponding municipalities was used as a factor for the allocations.

With regard to the issue of scale, we used different spatial references for the nutrient budgets in the two case study areas. For the federal state of Schleswig-Holstein, we allocated the nutrient budgets solely to the corresponding municipalities. Thus, the resolution of the result corresponds to the resolution of the input data, the *Landwirtschaftszählung* (Statistikamt Nord 2010). In order to allow for comparability, we used the same approach in the Bornhöved Lakes District. However, in addition to that, aiming to assess the smaller case study area in more detail, we allocated the nutrient budgets to the respective areas within each municipality.

Organic fertiliser from livestock

The calculation of the nitrogen content of organic fertiliser from livestock was based on data from the Statistikamt Nord (2010), collected within the framework of the *Landwirtschaftszählung* 2010. The level of detail of the data varied - from *Großvieheinheit* (GVE)[*15] over main livestock species to a precise register of all livestock, taking age and purpose of livestock into account. In order to ensure an optimal accuracy but also to prevent data complexities, data on the main livestock species were selected. In order to obtain the total amount of nitrogen used in the form of organic fertiliser, specifications of the nitrogen content of manure specified for the different evaluated livestock species were needed. For that, appendix five of the German fertiliser ordinance (DüV 2007) was accessed. However, the classification of livestock strongly differs in several points from the livestock classification given by the statistical data. Therefore, it was more convenient to

refer to the following publication with regard to the reference values of nitrogen concentrations in manure: *Richtwerte für die Untersuchung und Beratung zur Umsetzung der Düngeverordnung in Mecklenburg-Vorpommern* (Table 53) by the Ministerium für Landwirtschaft, Umwelt und Verbraucherschutz Mecklenburg-Vorpommern (2008)[*16]. Still, some values needed to be calculated through averaging and/or summing up reference values of different categories because the classification did not correspond to the classification of the statistics precisely enough (Suppl. material 1).

Digestate from biogas plants

The substances used as substrate for biogas production in Schleswig-Holstein (manure, corn silage, cereal, grass silage, bio waste and remnants) were adopted from Taube et al. (2013). In conformity with Taube et al. (2013), the share of nitrogen from manure in the digestate was neglected in order to prevent double-counting. Taube et al. (2013) expect 5% nitrogen losses through storage. Taking this nitrogen loss into account, Taube et al. (2013) calculated that approximately 74 tonnes of nitrogen per megawatt installed electric power are generated in Schleswig-Holstein. By combining the data from Taube et al. (2013) with information on average biogas plant outputs in Schleswig-Holstein (Agentur für Erneuerbare Energien e.V 2017[*17]) and general information on the performance of biogas plants (Bayerische Landesanstalt für Landwirtschaft 2008[*18]), the overall nitrogen content of the digestate in Schleswig-Holstein in 2010 and the average nitrogen content per year and biogas plant were calculated.

Biological nitrogen fixation

Data from the *Landwirtschaftszählung* 2010 (Statistikamt Nord 2010)[*19] served as the basis for the calculation of the biological nitrogen fixation. The extent of grassland in each municipality was multiplied by the nitrogen fixation efficiency (Landwirtschaftskammer Niedersachsen 2017a[*20]). The Landwirtschaftskammer Niedersachsen (2017a) differentiates between varying shares of legumes in the grassland (between 5 and 40 %). The values of nitrogen fixation concerning the shares of legumes were averaged. The result was multiplied by the area of grassland in each municipality. Data on the cultivation of legumes was only available for counties and the computed amount of nitrogen fixation through legumes added up to less than 0.2 kilograms of nitrogen per hectare. Therefore, nitrogen fixation through pure legume cultivation was neglected.

Sewage sludge

Data on the amount of sewage sludge applied to agricultural soils in Schleswig-Holstein was available for the year 2011 by Kleinhans (2013) from the MELUR. In order to obtain data on nitrogen input through sewage sludge in agricultural fields, a reference value for the nitrogen content in sewage sludge was taken from Taube et al. (2013) and multiplied with the amount of sewage sludge. We divided the total nitrogen content by the agricultural area of Schleswig-Holstein. The result shows the average amount of nitrogen input per hectare on agricultural soils in Schleswig-Holstein.

Compost

As no statistical data was found on the quantity of compost applied to agricultural soils in Schleswig-Holstein, the values computed by Heidecke et al. (2012) were used in this study. The authors determined the average amount of nitrogen input per hectare on agricultural soils in Schleswig-Holstein through the application of compost.

Nitrogen deposition

The data on nitrogen deposition in 2009 was provided by the UBA (2015). The data was available for all of Germany. The total nitrogen deposition values combine wet, dry and occult nitrogen deposition. Differentiating ten different land use types (grassland, semi-natural, arable, permanent crops, coniferous forest, deciduous forest, mixed forest, water, urban and others), spatially differentiated deposition values were available for the whole study area.

Yield

Information on the area used for the different crop types was available from the *Landwirtschaftszählung* 2010 (Statistikamt Nord 2010), on the spatial scale of municipalities. However, no precise information was given on the actual yield. Yield quantity was only available for higher administrative units. In order to enable the calculation on the level of municipalities, the average yield (t/ha*year) was calculated for each crop type. We then multiplied the outcome by the data available at the municipality level. Specifications of the nitrogen content of the evaluated crop plants were also needed and were taken from the DüV (2007)[*21]. In the DüV (2007), the authors distinguish between different crude protein contents for each crop type. As this information was not available for the crops in Schleswig-Holstein, average values were selected. Suppl. material 2 lists the values utilised for the calculation of the nitrogen content per crop type. The specified nitrogen content per crop type was defined as the nitrogen content which is removed as primary or secondary product from the field. Thus, the nitrogen content of standard remnants was not included in the analysis (KTBL 2009).

Loss of nitrogen in organic fertiliser from stable, storage and application

According to the Landwirtschaftskammer Niedersachsen (2017b)[*22], which refers to the DüV (2007), the application and the input of nitrogen from organic fertiliser (manure) can be differentiated. The application of organic fertiliser from livestock considers nitrogen losses which are attributed to losses in the stable and losses resulting from the storage of fertiliser. In contrast to that, the input of nitrogen from organic fertiliser also considers nitrogen losses which occur during the application of the fertiliser. The Landwirtschaftskammer Niedersachsen (2017b) differentiates the nitrogen loss factor between different manure types (e.g. liquid manure and solid manure). For this study, average loss values for all manure types were taken into account (Suppl. material 3).

Loss through application of mineral fertiliser

We used the data computed by Heidecke et al. (2012) and calculated a loss rate based on the nitrogen budget for 2010 on the level of municipalities in Schleswig-Holstein.

No specifications on import and export of fertilisers were available on the relevant spatial scales. Therefore, the nitrogen budget was computed assuming that no import and export occurred. The same applies for digestate from biogas plants. The final budget calculation is similar to the formula used by Bach (Taube et al. 2015, Bach et al. 2014). However, because our parameters differ from the parameters selected by Bach et al. (2014), the formula was slightly modified, resulting in the following:

> Budget = Mineral Fertiliser + Organic Fertiliser + Digestate (excl. Manure) + Biological Fixation + Nitrogen Deposition + Compost + Sewage Sludge - Yield - Loss of Organic Fertiliser (Stable, Storage and Application) - Loss of Mineral Fertiliser (Application)

The nitrogen status

In order to assess the potential ecosystem service supply and demand, two more important datasets were collected: groundwater nitrate concentration and the nitrate leaching potential. After nitrogen is introduced into the environment, the potential for the ecosystem to regulate nitrogen inputs influences the quantity of nitrogen available for nitrate leaching. However, the actual nitrate leaching is also dependent on other factors. The *Landesamt für Landwirtschaft, Umwelt und ländliche Räume* (LLUR 2011a) assessed the nitrate leaching potential in Schleswig-Holstein. According to the LLUR (2011a), the following factors are relevant for computation: soil type and texture, soil horizon classification, humus content, state of decomposition, state of consolidation, substance volume, leak water rate, mean capillary rise, precipitation and the climatic water balance. The data were classified into categories from one to five, whereby five represents the highest nitrate leaching potential. Data on the measured nitrate concentration in the groundwater bodies in Schleswig-Holstein were downloaded from the online portal "*Wasserkörper- und Nährstoffinformationssystem Schleswig-Holstein*" (MELUR 2016) for the year 2013. In order to obtain continuous spatial data, the measured values were interpolated using the IDW interpolation method (software: ArcMap 10.3).

The measured groundwater nitrate concentration was defined as the focal indicator for the nitrogen status in the study area. The influence of the ecosystem service nutrient regulation, the nitrate leaching potential and the actual nitrogen budget on the nitrogen status in the study area was tested. In order to analyse this relationship statistically, the correlations between the parameters were calculated for Schleswig-Holstein and the Bornhöved Lakes District. In order to assess the issue of scale and spatial resolution, in total five different datasets (Table 3) were statistically analysed.

A rank-order correlation analysis was executed, whereby the parameters groundwater nitrate concentration, nitrogen budget, nitrate leaching potential and nutrient regulation

potential were incorporated. According to literature, the following correlations were expected: nitrogen surpluses correlate positively to the groundwater nitrate concentration (Wick et al. 2012, Power 2010, Rumohr et al. 1996, European Council 1991, Tivy 1987). In addition to that and in consistency with the assumptions and definitions given in this study, a negative correlation was expected between the nutrient regulation potential and the groundwater nitrate concentration (Gaines and Gaines 1994). As explained earlier, the LLUR assessed the nitrate leaching potential incorporating several site-specific characteristics. Thus, we expect that a positive correlation exists between the nitrate leaching potential and the groundwater nitrate concentration. As a consequence, a negative correlation presumably will arise between the nitrate leaching potential and the nutrient regulation potential. The correlation between the nitrogen budget and the nutrient regulation potential allowed us to draw conclusions on the coincidence of ecosystem service potential supply and demand.

Table 3.

Datasets used for the statistical analysis.

Dataset	Study area	Grid/ Scale*23	Budget reference
SH_M	Schleswig-Holstein	Municipalities	Municipalities
SH_LG	Schleswig-Holstein	Large grid	Municipalities
B_LG_B2	Bornhöved Lakes District	Large grid	Municipalities
B_LG_B4	Bornhöved Lakes District	Large grid	CORINE Land Classes
B_FG_B4	Bornhöved Lakes District	Fine grid	CORINE Land Classes

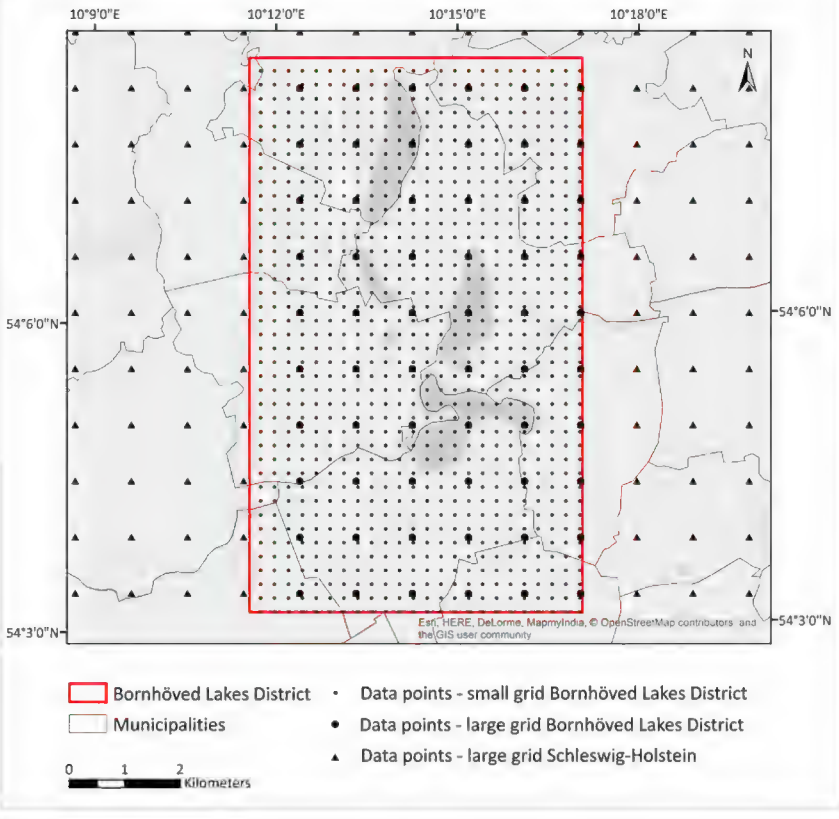

Figure 5.

Assessment units for Schleswig-Holstein and the Bornhöved Lakes District: Large and fine point grid (data on administrative boundaries from GeoBasis-DE / BKG 2017b).

First, the statistical analysis was executed for average values from each municipality. Second, the same analysis was executed using an original values excerpt via a point grid (approximately 1 kilometer spacing). A spatially more explicit analysis was executed for the Bornhöved Lakes District case study area. Here, the nitrogen budget was allocated to the corresponding CORINE land cover classes, thereby generating a spatially more explicit demand for nutrient regulation. In addition to the point grid, an additional finer point grid was created with approximately 250 m spacing (Fig. 5). The rank-order correlation analysis was repeated for these datasets.

Fig. 6 gives a schematic overview on the workflow to compute potential supply and demand for the ecosystem service nutrient regulation and on the statistical analyses.

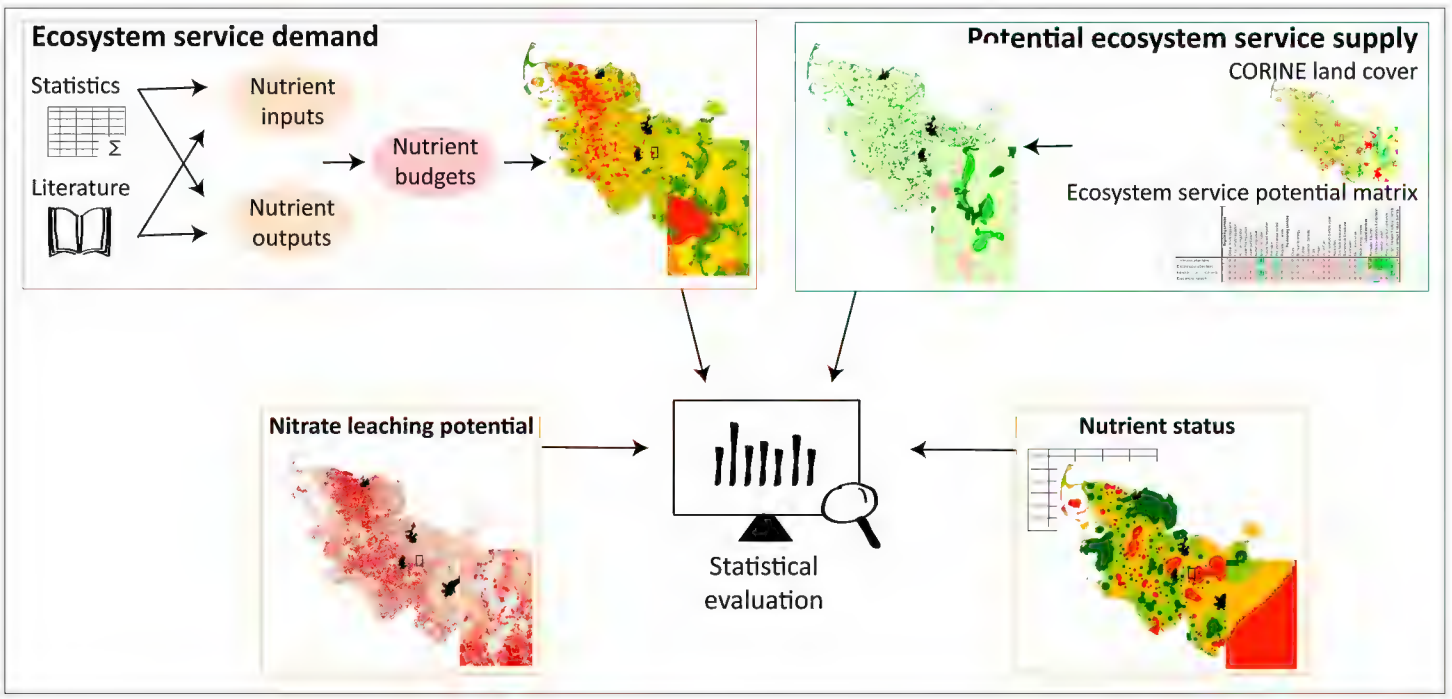

Figure 6.

Overview of the methodological procedure for the assessments of the ecosystem service nutrient regulation and the nutrient status on the two scales Schleswig-Holstein and Bornhöved Lakes District (CORINE = Coordination of Information on the Environment[*24]).

Results

Supply of nutrient regulation

The potential supply of the nutrient-regulating ecosystem service was evaluated and mapped for Schleswig-Holstein and the Bornhöved Lakes District using the ecosystem service matrix (Burkhard et al. 2014) based on CORINE land cover types (Fig. 4). The qualitative values on nutrient regulation for the matrix assessment have been adopted from Burkhard et al. (2014) (p. 15). In Table 4, the relevant values are shown. Fig. 7 shows the spatial distribution of the ecosystem service nutrient regulation potential supply.

Table 4.

Adopted ecosystem service potential supply values for nutrient regulation. Scale 0 = no relevant potential; 1 = low relevant potential; 2 = relevant potential; 3 = medium relevant potential; 4 = high relevant potential; 5 = very high (maximum) relevant potential (based upon Burkhard et al. (2014)).

LULC classes	**Nutrient regulation potential**
Continuous urban fabric	0
Discontinuous urban fabric	0
Industrial or commercial units	0
Road and rail networks	0
Port areas	0
Airports	0
Mineral extraction sites	0
Dump sites	0
Construction sites	0
Green urban areas	2
Sport and leisure facilities	1
Non-irrigated arable land	1
Permanently irrigated land	1
Ricefields	1
Vineyards	1
Fruit trees and berries	2
Olive groves	1
Pastures	1
Annual and permanent crops	1
Complex cultivation patterns	1
Agriculture & natural vegetation	2
Agro-forestry areas	2
Broad-leaved forest	5
Coniferous forest	5
Mixed forest	5
Natural grassland	4

Moors and heathland	3
Sclerophyllous vegetation	2
Transitional woodland shrub	2
Beaches, dunes and sand plains	1
Bare rock	0
Sparsely vegetated areas	1
Burnt areas	0
Glaciers and perpetual snow	0
Inland marshes	4
Peatbogs	4
Salt marshes	2
Salines	0
Intertidal flats	1
Water courses	3
Water bodies	3
Coastal lagoons	3
Estuaries	3
Sea and ocean	3

The largest part of the study area is characterised by low nutrient-regulating potentials (Fig. 7). High regulatory potentials are distributed rather patchily over Schleswig-Holstein. However, areas with high potentials are agglomerated in the south and southeast of the study area (Fig. 7). Consistent with the distribution of the nutrient regulation potential in Schleswig-Holstein, the largest part is also featured with rather low nutrient regulation potentials, with similar potentials also being evident in the Bornhöved Lakes District. Medium and high potentials can be found mainly in the central part of the area. There are also areas with no relevant nutrient regulation potential. These are distributed randomly throughout both study areas.

Demand for nutrient regulation

The largest oversupply of nitrogen can be found in municipalities located in the northwest of the study area (Fig. 8). An agglomeration of municipalities with relatively low nitrogen budgets (lower than 40 kilograms of nitrogen per hectare per year) is located in the southeast of the study area. With regard to the regional landscapes, municipalities in the *Geest* show a tendency for larger nitrogen surpluses. There, the nitrogen budget increases from south to north. In the Bornhöved Lakes District, the majority of municipalities have a

nitrogen budget lower than 40 kilograms per hectare per year. Municipalities with higher nitrogen budgets can be found in the west of the study area. The municipality with the highest nitrogen surplus is Ruhwinkel. Compared to the adjacent municipalities, Ruhwinkel is featured by relatively high nitrogen inputs through the application of digestate and organic fertilisers from livestock.

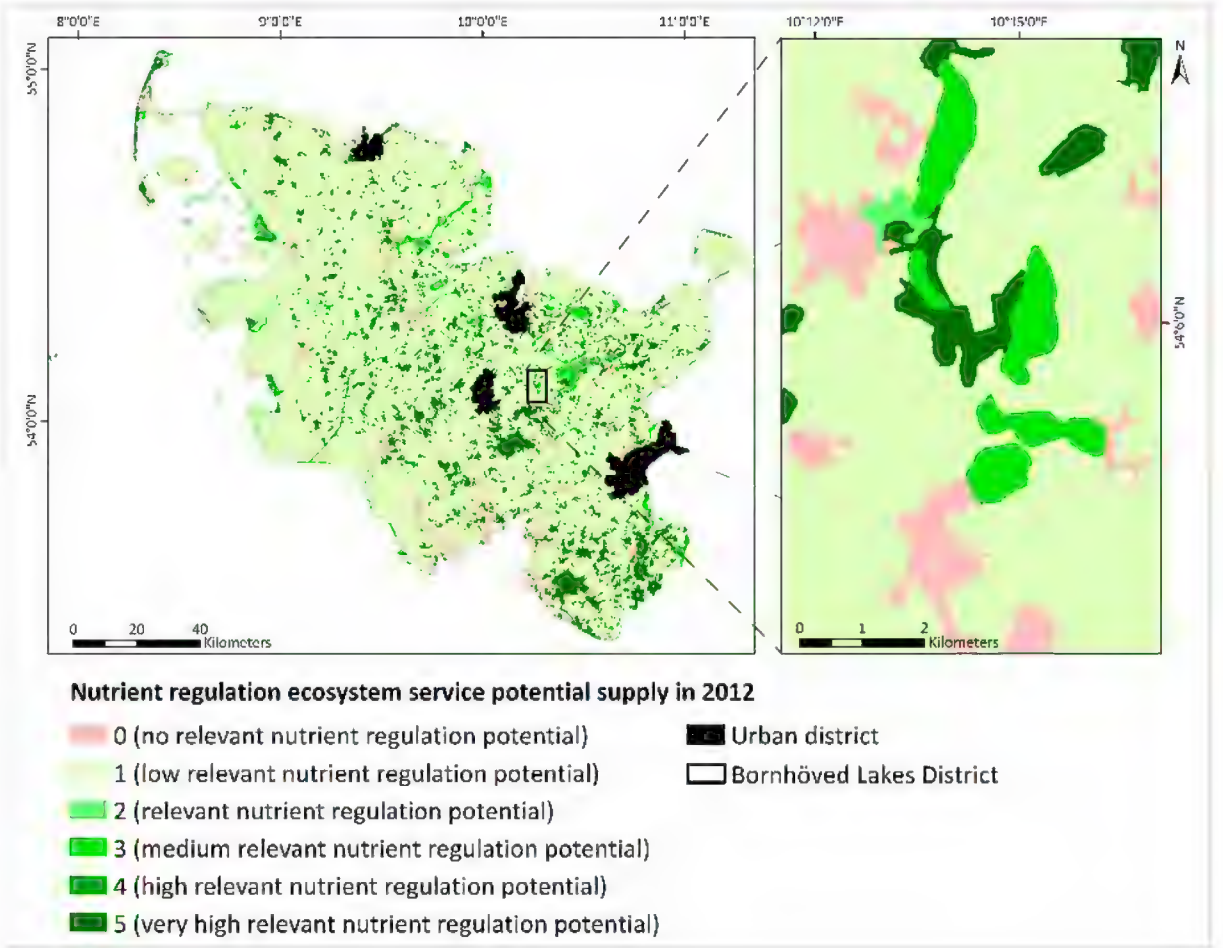

Figure 7.

Nutrient regulation ecosystem service potential supply in 2012 in Schleswig-Holstein (left) and the Bornhöved Lakes District (right) (application of ecosystem service potential matrix by Burkhard et al. 2014; CORINE Land Cover data from GeoBasis-DE / BKG 2017a).

For the Bornhöved Lakes District, the nitrogen budget was mapped in a spatially more explicit manner (Fig. 9). In the first step, the nitrogen budget was mapped excluding nitrogen deposition. Furthermore, the remaining nitrogen budget was not assigned to the corresponding municipalities, but assigned to the CORINE LULC classes “land principally occupied by agriculture” (243), “non-irrigated arable land” (211) and “pastures” (231) in the corresponding municipalities. Thus, areas with CORINE classes, other than these, have a nitrogen budget equal to zero. High nitrogen budgets (61 - 80 kg N/ha*year) can be found in the west of the Bornhöved Lakes District. Medium nitrogen budgets are located in the south; the remaining area shows low nitrogen budgets. In the next step, atmospheric nitrogen deposition was mapped separately. The greatest share of the area is characterised by nitrogen deposition rates between 16 and 18 kilogram nitrogen per hectare per year. Higher and lower nitrogen deposition values are distributed rather randomly throughout the study area. In the third and last step, both values were combined in order to obtain the total nitrogen budget. The largest share of the area shows medium

nitrogen budgets (41 – 60 kg N/ha*year). Very low and low budgets are distributed randomly throughout the Bornhöved Lakes District and can be found along the eastern border of the study area, respectively. High nitrogen budgets are located in the southwest and southeast. The relatively high nitrogen inputs on the agricultural grounds that belong to the municipality of Ruhwinkel can still be identified.

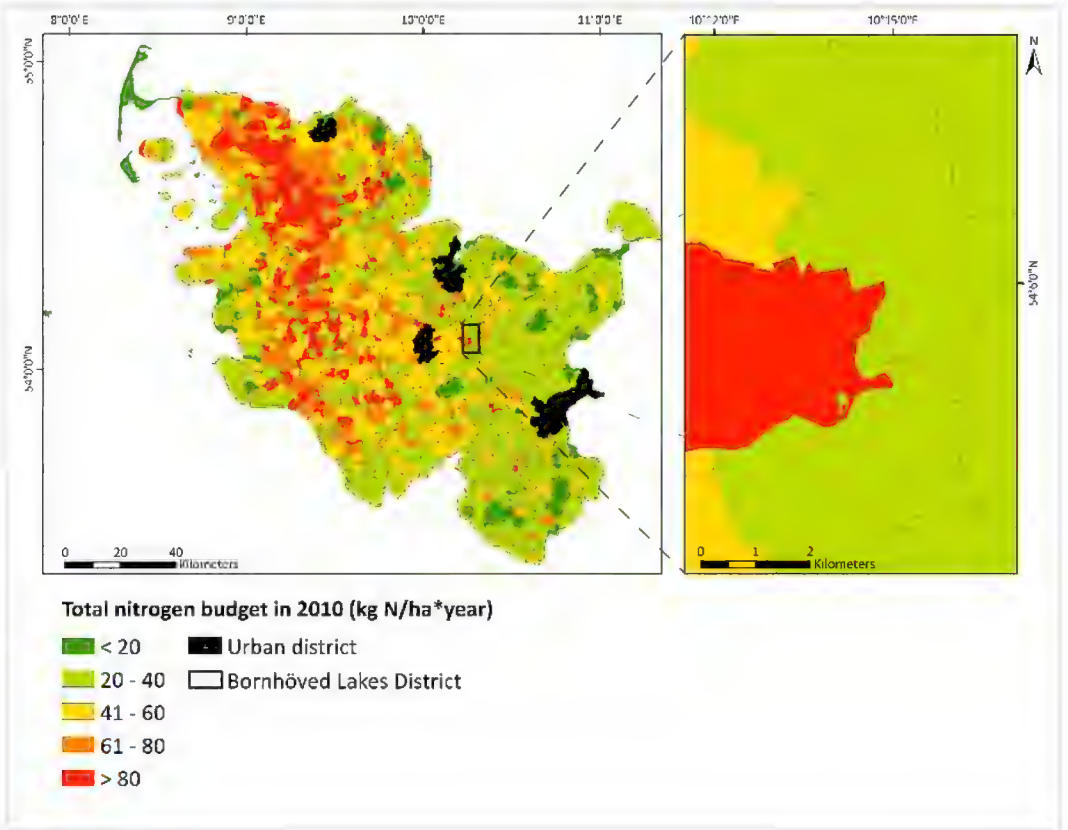

Figure 8.

Total nitrogen budget in 2010 in Schleswig-Holstein Holstein (left) and the Bornhöved Lakes District (right) on the municipality scale (data on agricultural census 2010 from Statistikamt Nord 2010[*25]; data on nitrogen deposition 2009 from UBA 2015; data on administrative boundaries from GeoBasis-DE / BKG 2017b).

The nitrogen status

Consistent with Taube et al. (2015) and the Nitrate Directive (European Council 1991), the groundwater nitrate concentration was selected as the focal indicator for the nitrogen status of the environment. It can be assumed that responses to changing parameters (i.e. nitrogen budget) can be detected in the measured nitrate concentration after a specific time lag (Rumohr et al. 1996). In order to take that time lag into account and remain in accordance with recent publications on the nutrient status of Schleswig-Holstein (e.g. Taube et al. 2015), data from 2013 was selected.

In 2013, the groundwater nitrate concentration was distributed rather heterogeneously (Fig. 10). Lowest concentrations (<10 mg/l) were found in the northeast (from Flensburg to Eckernförde) of Schleswig-Holstein and along the central part of Schleswig-Holstein's North Sea coastline. Hotspots of nitrate concentrations were distributed rather patchily throughout the federal state, mostly in the hinterland. The largest area with relatively high nitrate concentrations (>50 mg/l) was located in the east of Schleswig-Holstein. In the

remaining part, medium concentrations (10-50 mg/l) were mostly dominant. The Bornhöved Lakes District is located at the western boundary of the largest hotspot. Thus, high nitrate concentrations (>50 mg/l) were found in approximately half of the case study area. From southeast to northwest, the nitrate concentrations decreased. However, only a very small part of the Bornhöved Lakes District showed low nitrate concentrations (<10 mg/l).

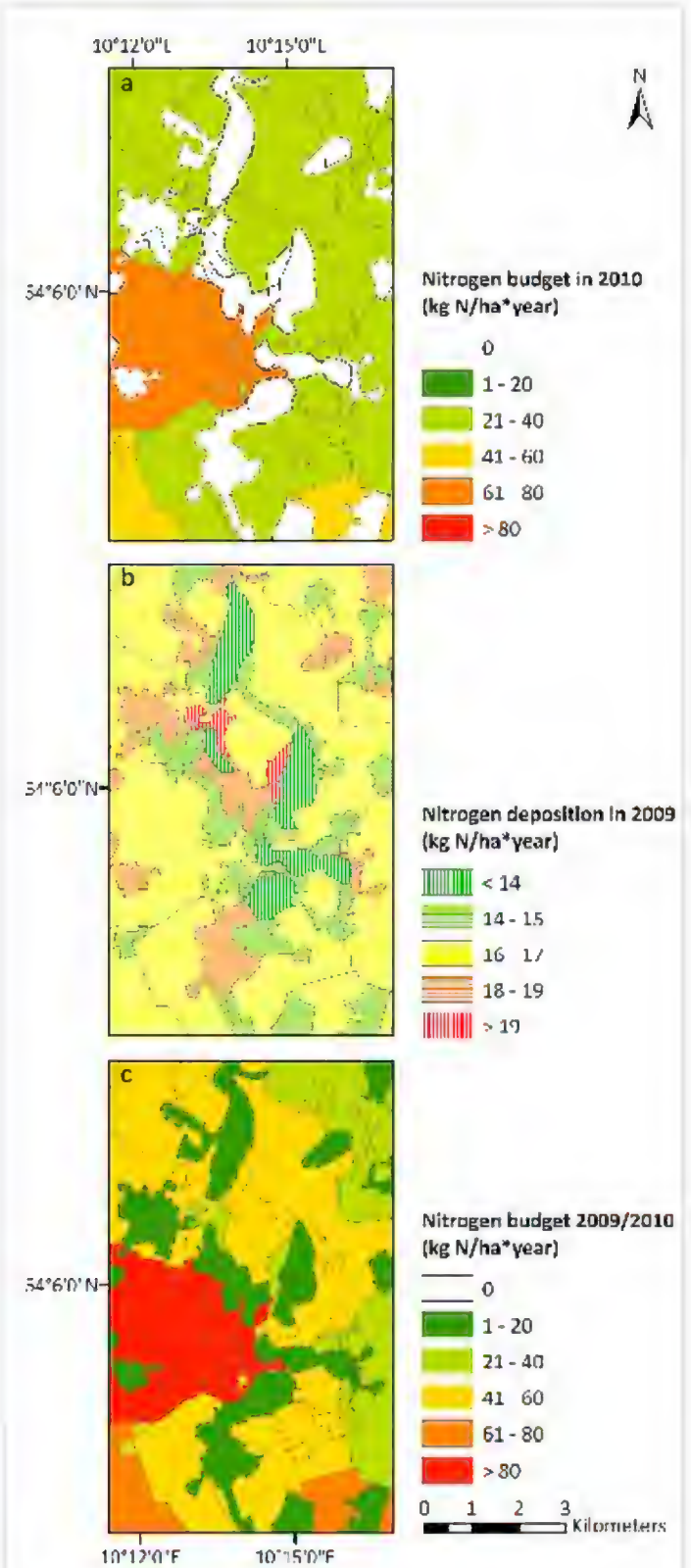

Figure 9.

Nitrogen budgets in the Bornhöved Lakes District: (a) nitrogen budget 2010 (excl. nitrogen deposition) for each municipality allocated to arable land, (b) atmospheric nitrogen deposition in 2009, (c) total nitrogen budget 2009/2010 (data on agricultural census 2010 from Statistikamt Nord 2010[*26]; data on nitrogen deposition 2009 from UBA 2015).

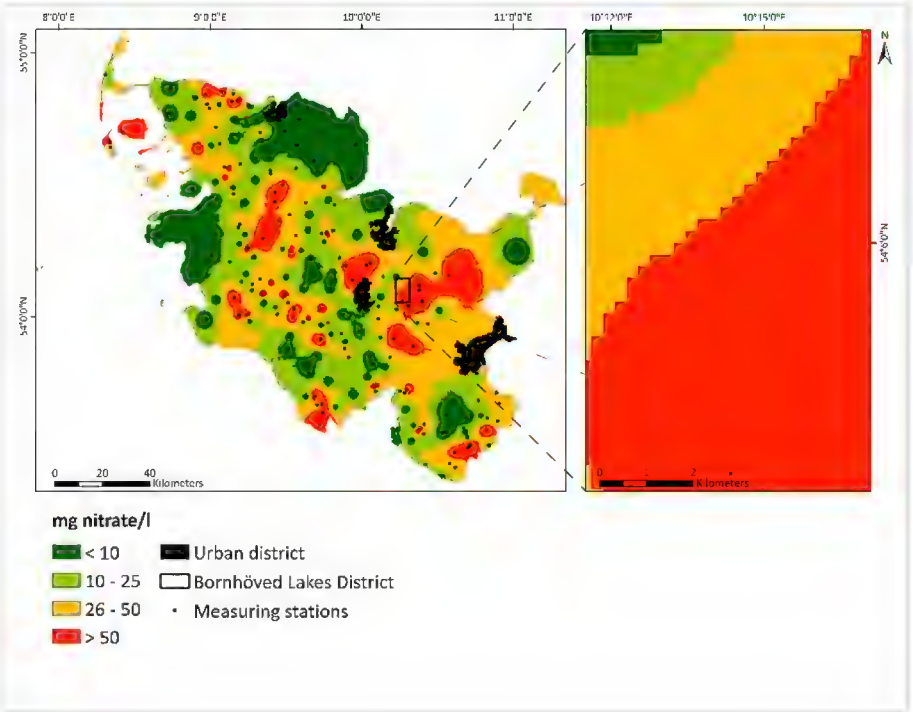

Figure 10.

Interpolated groundwater nitrate concentration in Schleswig-Holstein (left) and the Bornhöved Lakes District (right) in 2013 (data from W*asserkörper- und Nährstoffinformationssystem Schleswig-Holstein* from the MELUR 2016).

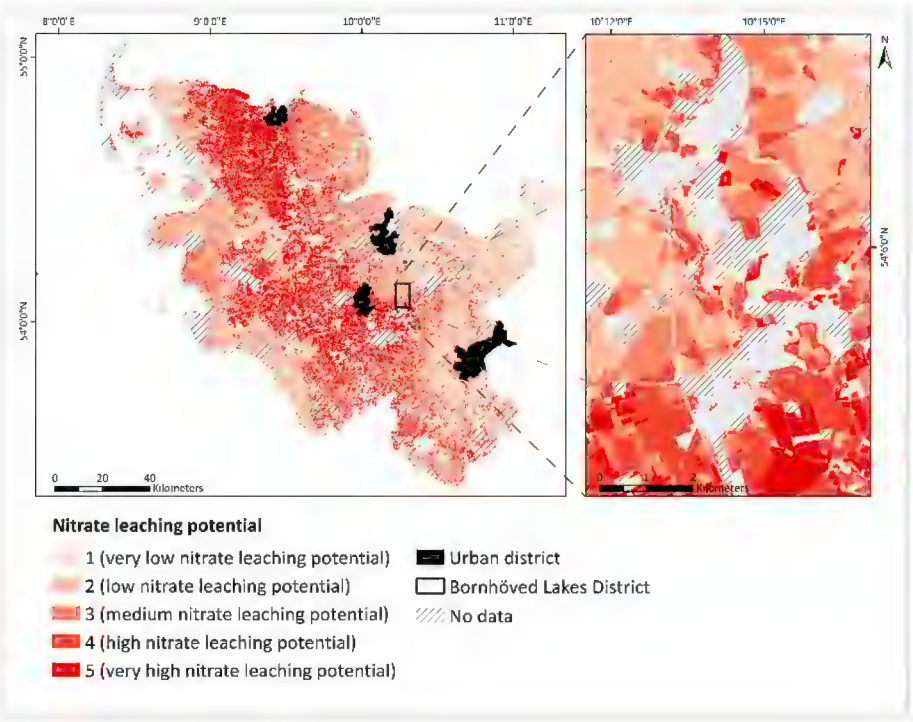

Figure 11.

Nitrate leaching potentials in Schleswig-Holstein (left) and the Bornhöved Lakes District (right) (data from LLUR 2011b).

Low nitrate leaching potentials can be found along both coastlines of Schleswig-Holstein (Fig. 11). Lowest potentials agglomerate at the central part of the Baltic Sea coastline. High potentials are located in the hinterland, increasing from south to north. Thus, the area with high potentials coincides with the spatial extent of the *Geest*. In accordance with this pattern, in the Bornhöved Lakes District, the potential decreases from south to north (Fig. 11).

Statistical evaluation

In contrast to the datasets for the area of Schleswig-Holstein, all datasets on the scale of the Bornhöved Lakes District revealed a negative correlation between the nutrient regulation potentials and the groundwater nitrate concentrations (Fig. 12). For all of these datasets, the correlations are calculated to be significant at the 0.05 level. In addition, for all datasets on the scale of the Bornhöved Lakes District, stronger positive correlations were found between the nitrate leaching potential and the groundwater nitrate concentration compared to the Schleswig-Holstein datasets. As expected for these datasets, negative correlations exist between the nitrate leaching potential and the nutrient regulation potential, even though none of these correlations is statistically significant. Except for the dataset on the municipality scale (SH_M), the correlation analysis revealed negative correlations between the nitrogen budgets and the groundwater nitrate concentrations. Both datasets for the area of Schleswig-Holstein reveal a very weak negative correlation between the nitrogen budget and the nutrient regulation potential. Focusing on to the Bornhöved Lakes District, the dataset with the lowest resolution (BLD_LG_B2) indicates a positive correlation between these two variables. However, for both Bornhöved Lakes District datasets, including the spatially more explicit nitrogen budget (BLD_LG_B4 and BLD_FG_B4), stronger negative correlations can be found between the nitrogen budget and the nutrient regulation potential. Only for the dataset with the highest spatial resolution can this correlation befound significant.

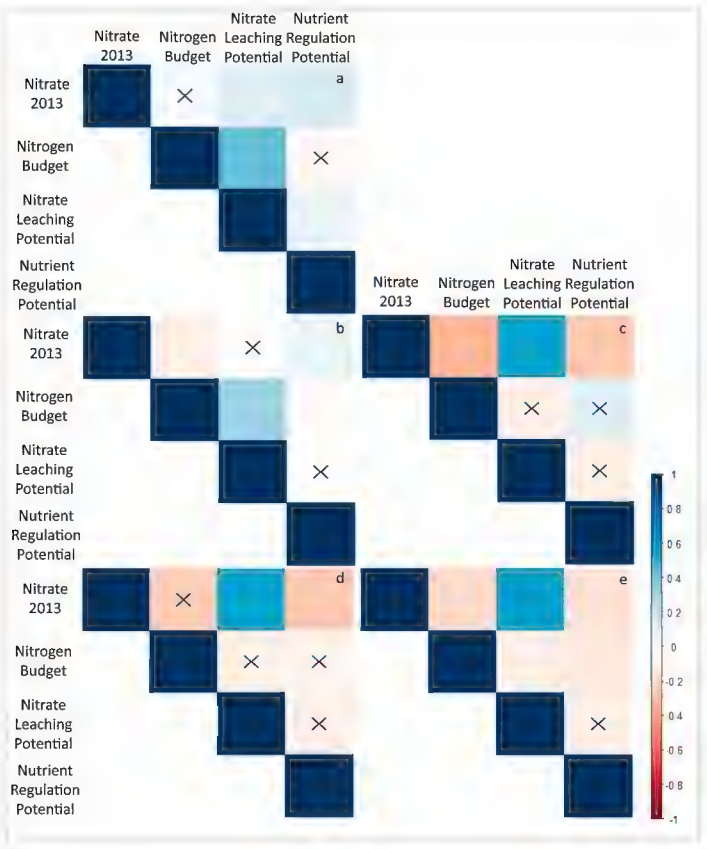

Figure 12.

Correlograms for each dataset (a: SH_M; b: SH_LG; c: B_LG_B2; d: B_LG_B4; e: B_FG_B4; for explanation see Table 3) including nutrient regulation potentials, nitrate leaching potentials, nitrogen budgets and groundwater nitrate concentrations (cross indicates insignificant correlation at the 0.05 level).

Discussion

Spatial distribution of supply and demand potentials

The potential supply of nutrient regulation seems to be distributed randomly throughout the study areas Schleswig-Holstein and Bornhöved Lakes District. Small- and medium-sized patches of high nutrient regulation potentials are scattered throughout a landscape dominated by low nutrient regulation potentials. The biogeochemical properties of different nutrients vary and, as a result, the corresponding processes in the environment also change. For reasons of simplification, we analysed the ecosystem service nutrient regulation by using the nutrient nitrogen as an example. Here, one must note that the potential supply values for nutrient regulation which have been adopted from the expert-based assessment by Burkhard et al. (2014), do not differentiate between different nutrients. The potential supply is thus not specifically harmonised for nitrogen but depicts a more general trend. Furthermore, the spatial distribution modelling was solely dependent on the primary vegetation and land use pattern, because the potential supply of nutrient regulation was mapped qualitatively based on the matrix values provided by Burkhard et al. (2014) and CORINE land cover classes. As nutrient regulation is dependent on further parameters such as soil type, texture and moisture, it is questionable whether the allocation of nutrient regulation potentials, based solely on land cover classes, is sufficient in order to characterise local conditions and nutrient regulation is dependent. However, this approach is an efficient way to gain an overview of the investigated study areas. The quantification of the demand for nutrient regulation on the municipality scale supports the assumption by Taube et al. (2015) on the regional differentiation of the nitrogen budget in Schleswig-Holstein. A tendency for higher nitrogen budgets in the west of the study area was identified, which partly confirms the nitrogen budgets published by Taube et al. (2015) (p. 19). In addition, the relative distribution of the nitrogen budget, to a large extent, conforms to the nitrogen budget calculated on the scale of landscape forms, published by Taube et al. (2015) (p. 20). In the Bornhöved Lakes District on the municipality scale, high nitrogen budgets were found in the west. The greatest share of the area had relatively low nitrogen budgets (<40 kg N/ha*year). However, the spatially more explicit nitrogen budgets revealed a more heterogeneous picture. Low nitrogen budgets (<40 kg N/ha*year) could only be found along the eastern border of the study area and in small fragments throughout the Bornhöved Lakes District. High nitrogen budgets (>60 kg N/ha*year) could still be found in the west but also in the southeast of the study area. The remaining area showed medium nitrogen budgets (41-60 kg N/ha*year).

With respect to nitrogen budgets, the following aspects need to be kept in mind: The computation of the nitrogen budget is highly dependent on input data. Most parameters were based on the data of the *Landwirtschaftszählung* 2010 (Statistikamt Nord 2010[*27]). Due to data privacy, the agricultural census data on the scale of municipalities was not complete, as some data had been censored. The data had been corrected on the municipality scale in order to obtain more realistic results. Still, the correction factor for the municipalities is solely based on the extent of the agricultural area in the corresponding

municipality. This extrapolation may downgrade the obtained results. The parameters relevant for the nitrogen budget could be calculated by employing different calculation techniques and methodologies. Thus, the nitrogen budgets are influenced by the selected approach. For instance in this study, nitrogen inputs from organic fertilisers (livestock) were corrected by stable, storage and application losses, as the DüV (2007) allows the input values to be corrected by these parameters, even thoughthese emissions will also end up in a waterbody, eventually. The same is true for the deduction of nitrogen losses through the application of mineral fertilisers.

The methodology employed for the calculation of mineral fertiliser inputs was adopted from Taube et al. (2015) (p. 14) which is based upon Bach et al. (2014) (p. 18) and consists of a calculation which estimates mineral fertiliser quantities in relation to the quantities of organic fertiliser, digestate, biological fixation and yield for the area of Schleswig-Holstein in 2010. The approach by Taube et al. (2015) is based on data from 416 model farms (adapted from 14,700 real farms – InVeKoS[*28] data, https://www.zi-daten.de/). Taube et al. (2015) claim to provide a more realistic nitrogen budget. However, their input data and model were not available for this research. Thus, this methodology could not be adopted for comparison.

One must also keep in mind that, for the calculation of the nitrogen input through biological nitrogen fixation, the nitrogen fixed by legume cultivation was neglected because the relevant data was not available on the municipality scale but only on the county scale and only added up to 0.2 kilograms of nitrogen per hectare in 2010. Another point of potential criticism may arise from the fact that the analysis of this study did not consider seasonal variability. Rumohr et al. (1996) report, amongst others, on the seasonal variability of groundwater nitrate concentrations in the Bornhöved Lakes District. The variability can primarily be attributed to the diverging nitrogen assimilation through plants throughout the year (Rumohr et al. 1996). None of this information could be checked by this study.

Nutrient status and statistical evaluation

The groundwater nitrate concentrations, which served as indicators for the nutrient status, were found to be distributed heterogeneously. The distribution partly followed a trend expected from the distribution of the nitrate leaching potential and the computed nutrient budget. In the north and west of the federal state, the occurrence of high groundwater nitrate concentration was roughly located in areas with high nutrient budgets and high nitrate leaching potentials. These conditions were particularly found in the area of the *Geest*. Conforming to the poor sandy soils of the *Geest* area, the nitrate leaching potentials were relatively high. The same co-occurrence was found for low concentrations and potentials.

In the eastern part of Schleswig-Holstein, the groundwater nitrate concentration cannot be easily explained by the distribution of the nitrogen budget and nitrate leaching potential. Even though, the area is characterised by low to medium nitrate-leaching potentials as well as relatively low nutrient budgets, a large area is featured by relatively high groundwater nitrate concentrations. As the Bornhöved Lakes District is located at the western boundary

of the hotspot, high groundwater nitrate concentrations (>50 mg/l) were found in approximately half of the case study area, declining from southeast to northwest. This trend follows the distribution of the nitrate leaching potentials. In order to find out more about the interrelations of the datasets, including the potential supply of the ecosystem service nutrient regulation, a statistical evaluation was performed in the form of a rank-order correlation analysis. The parameters, nitrogen budget, nutrient regulation potential, nitrate leaching potential and groundwater nitrate concentration, were correlated with each other for all different datasets (Fig. 12).

The correlation analysis revealed a positive correlation between the nitrate leaching potential and the groundwater nitrate concentration. This correlation was expected. For the Bornhöved Lakes District, this correlation was stronger than for the datasets covering the whole federal state. The correlation between nutrient regulation potential and the groundwater nitrate concentration only fulfilled the (expected) negative correlation for the Bornhöved Lakes District. As a consequence, the same was true for the correlation between the nitrate leaching potential and the nutrient regulation potential. It is noticeable that the spatially more explicit datasets indicated a negative correlation between the nitrogen budget and the nutrient regulation potential. This correlation implies that there is a spatial mismatch between the ecosystem service potential supply and demand in the study area. The more aggregated nitrogen budget datasets suppress this condition. However, the statistical analysis could not prove the expected positive influence of the nitrogen budget on the groundwater nitrate concentration. This circumstance provokes the question whether thegroundwater nitrate concentration dataset is suitable as a nitrogen status indicator as the opposite effect could be expected from existing knowledge (Wick et al. 2012).

Previous publications (Taube et al. 2015, Rumohr et al. 1996) and Directives have specified groundwater nitrate concentration as an indicator for the nitrogen status of an area. On this account, the same indicator was selected for this research. Official data on groundwater nitrate concentrations at the measuring stations was provided by the MELUR (2016) in the online portal *Wasserkörper- und Nährstoffinformationssystem Schleswig-Holstein*. Thus, the same data on nitrate concentrations in Schleswig-Holstein's groundwater bodies as in previous studies were used in this study. The data available from the measuring stations was interpolated (employed interpolation method: IDW) for the whole study area. The fact that this indicator is not based on a spatially continuous original dataset but only on approximately 230 values (measuring stations) for the whole area of Schleswig-Holstein has to be considered a limitation. This limitation became even more evident for the Bornhöved Lakes District, because only one original data point is located within the study area (Fig. 10). The surrounding area of the Bornhöved Lakes District with high groundwater nitrate concentrations is also featured by only a few measuring stations. This circumstance decreased the certainty and the accuracy of the extent of the groundwater nitrate concentration hotspots and may lead to incorrect correlations with regard to the nutrient status. Rumohr et al. (1996) measured groundwater nitrate concentrations in the Bornhöved Lakes District in the first half of the 1990s at eight measuring stations. They discovered that the groundwater nitrate concentrations on agricultural grounds were higher compared to other ecosystems. It can be assumed that the results of the statistical analysis

with such accurate data on the current groundwater nitrate concentrations would correspond better with the expected values. Besides, the diverse measurement and quantification units of the different parameters also decrease the explanatory power of the statistical analysis. In particular, the comparison between physical entities (i.e. kilogram nitrogen per hectare per year) and the specification of nutrient regulation potential and nitrate leaching potential on a relative scale from zero and one to five, can lead to decreasing quality of the outcomes.

Still, by evaluating the results of the statistical analysis, it was possible to rank the relative validity of the results according to the spatial resolution and scale/study area (Fig. 13). For that matter, the validity of the outcomes was defined as the degree of conformity of the results with the expectations gained from the literature review. The results on the smallest scale with the finest grid and the highest spatial differentiation were found to deliver the most valid results. Whereas the computation of average values on the municipality scale led to imprecise or even incorrect data. The fact that municipalities are administrative with no geological or natural units most likely emphasises the inexpediency of the averaged values.

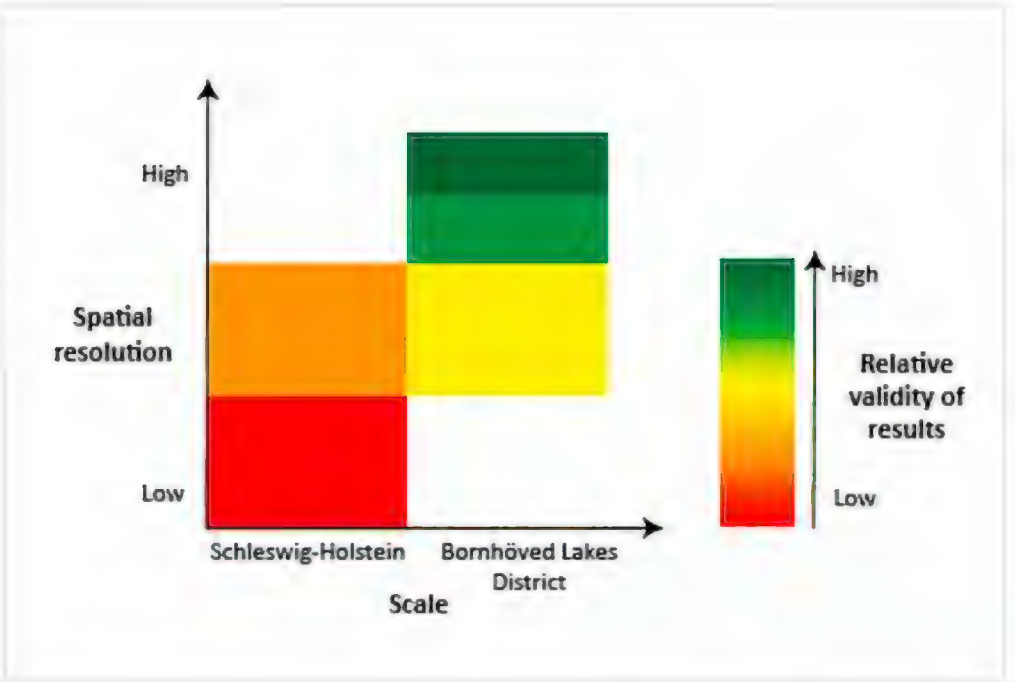

Figure 13.

Relative dependency between validity of results, scale and spatial resolution.

Relevance for land management and ecosystem service research

The results obtained by this research contribute to the recently ongoing debate on the topic of nutrient management. On the one hand, the research supports the suggested regional differentiation (Taube et al. 2015). On the other hand, the methodological uncertainties detected confirm the necessity for strict regulations with regard to the application as well as declaration of all kinds of fertilisers on farmland. In order to determine the value of this study for ecosystem service research, one needs to highlight the general picture rather than the explicit results obtained from this research. Contrary to the theoretical evaluation

of the ecosystem service concept, the integration of ecosystem services in applied sectors such as environmental management features challenges (de Groot et al. 2010). Egoh et al. (2007) state, amongst others, that the integration of ecosystem services into different research areas lags behind. Another gap exists between the theory and practice with regard to the quantification of ecosystem services (Crossman et al. 2013). Hou et al. (2013) go even further by pointing out uncertainties evolving from ecosystem services research on the landscape scale. Amongst others, uncertainties originate from respondents' preferences (in expert-based approaches), initial data uncertainty, technical problems, methodological uncertainties and complexities of natural systems (Hou et al. 2013).

Burkhard et al. (2012a) executed research with regard to mapping of ecosystem service supply, demand and budgets. They state that the "[...] supply of multiple goods and services by nature should match the demands of society, if self-sustaining human-environmental systems and a sustainable utilization of natural capital are to be achieved" (Burkhard et al. 2012a, p. 1). According to them, suitable indicators are required and diverse datasets need be integrated for assessments of both supply of and demand for ecosystem services on different temporal and spatial scales. Methods for ecosystem service quantifications are diverse, from mapping, modelling and field measurements to expert opinion (see ESMERALDA[*29] project). According to Seppelt et al. (2011), the methodologies should be weighted differently according to the reliability of the data and results.

As specified in Chapter 2, ecosystem services are defined as the benefit human beings experience from the environment. The definition implies the existence of a demand by human society (Burkhard et al. 2012a). This study deals, to a great extent, with the identification of the demand for the ecosystem service nutrient regulation. Through the calculation of nutrient budgets in the study areas, nutrient surpluses were identified. As eutrophication has been recognised as a threat to society in research as well as in decision-making, the localisation of hotspots emphasises the demand for the ecosystem service nutrient regulation in the study areas. The practical implementation through this study confirms the constraints identified in current research (Schulp et al. 2014, Hou et al. 2013). Constraints arise from the usage of different methodologies and datasets for the computation of supply and demand of/for the ecosystem service as well as from the comparison of a rather abstract concept to specific data on nitrogen surplus. The results from the statistical analysis support this notion. In order to combat this issue, more research is necessary assessing the practical implementation of ecosystem services and, as specified by Hou et al. (2013), on ecosystem service assessments on the landscape scale in general.

Further research

In the meantime, it would be interesting to undertake the calculation of mineral fertiliser according to Taube et al. (2015) on the municipality scale. Most likely, higher and more realistic mineral fertiliser quantities will emerge. More accurate information on fertiliser

usage will increase the validity of the results and thereby enhance the usability of resultsfor decision-making and sustainable land management. For future works, it is also of interest to assess the nutrient situation detached from administrative units, e.g. subdividing the study areas into catchment areas rather than municipalities. The outcome of the correlation analysis supports the usefulness of the transformation from administrative boundaries to natural boundaries. Besides, it would be interesting to assess the potential supply of nutrient regulation in more depth. A quantification of the potential nutrient regulation, incorporating side-specific characteristics such as data on soil types and textures, is an interesting approach, worthy of pursuing.

Conclusions

With regard to nutrient regulation in Schleswig-Holstein and the Bornhöved Lakes District, the potential supply and demand of/for nutrient regulation have been analysed using the example of nutrient nitrogen. Revising the objectives of the study, the following outcomes can be stated:

1. Assessing the potential supply and demand of/for nutrient regulation in the study areas. The greatest share of Schleswig-Holstein and the Bornhöved Lakes District are featured by a low potential supply of nutrient regulation. Areas with no or higher potential supply are spread out in patches of varying size throughout the study areas. In Schleswig-Holstein, a slight tendency for a greater share of relatively high potential supply can be detected in the southeast. In the Bornhöved Lakes District, there is a slight agglomeration of patches with higher potential supply in the centre and in the northeast. The distribution of the demand for nutrient regulation in Schleswig-Holstein indicates a clearer trend. Municipalities with low demand are located in the southeast. Municipalities with high values are agglomerated in the northwest of the study area. In the Bornhöved Lakes District, the demand for nutrient regulation is highest in the west. **Do potential supplies and demands of/ for nutrient regulation coincide in Schleswig-Holstein and the Bornhöved Lakes District**? No, in both study areas, relatively high demands for nutrient regulation coincide with low potential supplies of this ecosystem service.

2. Testing the statistical relationship amongst the nitrogen budget, nutrient regulation potential, nitrate leaching potential and the actual nutrient status of the study area.The statistical analysis implies that there is a positive relationship between the nitrate leaching potential and the groundwater nitrate concentration. Contrary to the data on Schleswig-Holstein, focusing on the Bornhöved Lakes District, the analysis revealed the expected negative relation between the ecosystem service potential nutrient regulation and the nutrient status. Contradicting the assumptions, the analysis cannot prove the positive effect of the nitrogen budget on the nutrient status. **Is it possible to prove the influence of the ecosystem service nutrient regulation on the nutrient status statistically**? Yes, but only for the smaller case study area, the Bornhöved Lakes District, where the statistical evaluation revealed

the regulative influence of the ecosystem service on the nutrient status defined as the groundwater nitrate concentration.

3. Giving useful advice on the usability of the different methodologies and scales assessed. When comparing the nitrogen budgets in the Bornhöved Lakes District on the municipality scale with the spatially more explicit nitrogen budgets, it can be stated that relevant information is lost through the aggregation according to administrative boundaries. Hotspots of high nitrogen budgets vanish and a relatively homogenous picture arises. It is relevant that the calculation and aggregation of environmental data on administrative units were accompanied by a loss in accuracy and even validity of the data. In this study, such an aggregation led to incorrect assumptions on the correlations between relevant parameters. In order to prevent data falsification, original data resolution should be retained. In addition, the study has shown that, by increasing the spatial differentiation of the input data, the validity of the results is improved to a large extent. In addition, a decrease in grid size influenced the results positively. However, this occurred to a less extreme extent than the spatial differentiation of the input data. **Does higher resolution data result in more valid outcomes**? Yes, the evaluation of the results shows that by increasing the resolution of data, the results become more appropriate and applicable.

In this study, the theoretical concept of regulating ecosystem services was applied to a land management issue which is highly relevant for decision-making on the scale of the study area and beyond. The study gives insight into the nitrogen situation in landscapes of Schleswig-Holstein. The results confirm the recently ongoing debate on the issue of fertiliser usage with regard to the environmental burden as well as the regional differentiation. The application of the ecosystem service concept allowed the comparison of the potential nutrient regulation supply and demand and revealed general and specific spatial mismatches between both. Moreover, the study also ascertained a regional differentiation for this mismatch. The *Geest*, which is most vulnerable to nitrogen surpluses because of the poor sandy soils which add to the high nitrate leaching potential of the area, was identified as the hotspot for a diverging potential supply and demand of nutrient regulation. It is of great relevance to strictly regulate agricultural nutrient inputs through organic (livestock and digestate) as well as mineral fertilisers in order to attain sustainable land management which is mandatory for securing the functionality and quality of our environment, most notably our soils and water bodies, our food and health.

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Supplementary materials

Suppl. material 1: Nitrogen excretion of livestock doi

Authors: Bicking et al.
Data type: table
Brief description: Nitrogen excretion (in kg N/year) of livestock (data from the Ministerium für Landwirtschaft, Umwelt und Verbraucherschutz Mecklenburg-Vorpommern 2008)
Filename: Appendix 1.pdf - Download file (366.34 kb)

Suppl. material 2: Average yield of agricultural crops in Schleswig-Holstein in 2010 doi

Authors: Bicking et al.
Data type: table
Brief description: Average yield (in t/ha) of agricultural crops in Schleswig-Holstein in 2010 (data from Statistikamt Nord 2010), nitrogen content (in kg N/dt fresh weight) of crop plants (data from DüV 2007) and corresponding estimated nitrogen content per hectare.
Filename: Appendix 2.pdf - Download file (456.61 kb)

Suppl. material 3: Relevant nitrogen application and input rates doi

Authors: Bicking et al.
Data type: table
Brief description: Relevant nitrogen application and input rates considering nitrogen losses (data from Landwirtschaftskammer Niedersachsen 2017b).
Filename: Appendix 3.pdf - Download file (322.77 kb)

Endnotes

*1 eng.: State Agency for Agriculture, the Environment and Rural Areas
*2 http://ec.europa.eu/environment/nature/biodiversity/strategy/index_en.htm

*3 http://www.esmeralda-project.eu/

*4 eng.: Statistical Agency North
*5 eng.: uplands
*6 eng.: State Agency for Agriculture, the Environment and Rural Areas
*7 http://www.eea.europa.eu/data-and-maps/figures/corine-land-cover-types-2006

*8 eng.: agricultural census 2010 (Statistical Agency North)
*9 eng.: agricultural census 2010 (Statistical Agency North)
*10 eng.: Ministry of Agriculture, Environment and Consumer Protection in Mecklenburg-Vorpommern
*11 eng.: State Agency for Agriculture, the Environment and Rural Areas
*12 eng.: Ministry of Energy, Agriculture, the Environment and Rural Areas
*13 eng.: Chamber of Agriculture Lower Saxony
*14 eng.: German fertilizer ordinance
*15 eng.: livestock unit
*16 eng.: Ministry of Agriculture, Environment and Consumer Protection in Mecklenburg-Vorpommern
*17 eng.: Renewable Energies Agency
*18 eng.: Bavarian State Research Center for Agriculture
*19 eng.: agricultural census 2010 (Statistical Agency North)
*20 eng.: Chamber of Agriculture Lower Saxony
*21 eng.: German fertilizer ordinance
*22 eng.: Chamber of Agriculture Lower Saxony
*23 see Figs 3, 5
*24 http://www.eea.europa.eu/data-and-maps/figures/corine-land-cover-types-2006

*25 eng.: Statistical Agency North
*26 eng.: Statistical Agency North
*27 eng.: agricultural census 2010 (Statistical Agency North)
*28 eng.: Integrated Administration and Control System (IACS)
*29 http://www.esmeralda-project.eu/